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Abdulaziz A. S. Fayez

Institute of Astronomy and Geophysics Researches, King Abdulaziz City for Science and Technology, Saudi Arabia

Nassir S. Al-Arifi

King Saud University, Saudi Arabia

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ABDULAZIZ A. S. FAYEZ
E-mail: afayez@kacst.edu.sa
Institute of Astronomy and Geophysics Researches,
King Abdulaziz City for Science and Technology,
P. O. Box 6086, Riyadh 11442, Saudi Arabia

NASSIR S. AL-ARIFI
E-mail: nalarifi@ksu.edu.sa
Department of Geology, King Saud University,
P. O. Box 2455, Riyadh 11451, Saudi Arabia
Fax No.: 966-01-4676345

ABSTRACT

On August 3rd, 1993, a sequence of earthquakes began in the central part of the Gulf of Aqaba, northern Red Sea at the Aragonese Deep. The largest event (M_D = 5.5) on August 3rd had an origin time of 12:42:43.22 GMT, a latitude of 28.628° N and longitude 34.644° E. This event was followed by more than 15000 events greater than 2 magnitude with some felt earthquakes.

On the same spot, another sequence of earthquakes began late 1995. The largest event (M_D = 5.9) on November 22 had an origin time of 04:15:12.30 GMT, a latitude of 28.8° N and longitude 34.7° E. This event was followed by more than 8000 aftershocks (1.5 <M_D<5.9) in the next 100 days. The majority of seismic activity of this sequence is clustered in the area located between 28.6° N - 29.3° N and 34.6° E - 34.9° E.

Focal mechanism were investigated by using data set obtained from the Seismic Network of the Seismic Studies Center, King Saud University, Riyadh, Saudi Arabia and the National Seismic Network at Institute of Astronomy and Geophysics Researches, King Abdulaziz City for Science and Technology. The data set included P-wave first motions of significant earthquake activity in this sequences mainly.

A total of 67 events was selected for focal mechanism analysis. The P-wave data from the surrounding seismic networks were also utilized additionally. The structural picture revealed from the focal mechanism solutions shows that the area in general characterized by strike-slip and dip-slip faulting. The mechanism of the first consistent with left-lateral strike-slip on N-NE trending faults of the Dead Sea Transform System. The second consistent with normal faults that generally trend E-W.

The main objective of this work is to study the focal mechanism of the recent Northern Red Sea sequences of August 1993 and November 1995 and to associate these sequences with faulting types that were found before using different methods.

INTRODUCATION

The Gulf of Aqaba, northern Red Sea, has been considered as one of the most active seismic zones along the Dead Sea transform system in the 1980's and 1990's. The internal structure of the gulf consists of three major segments. This geometry, combined with the left-lateral motion along the Arabian plate boundary, results in deeps at step zones, namely Elat deep in the north, Aragonese deep in the central part of the gulf and Dakar and Hume deeps in the south (Fig. 1).

The seismicity of the Dead Sea transform is characterized by both swarm and mainshock-aftershock types of earthquake activities. The historical and instrumental seismic records indicate a seismic slip rate of 0.15 - 0.35 cm/year during the last 1000-1500 years, while estimates of the average Pliocene-Pleistocene rate are 0.7 - 1.0 centimeter/year (Garfunkel, 1981).

Tectonic and geological information attribute this swarm to sub-surface magmatic activities and consequent isostatic adjustments in the Gulf of Aqaba region. On spreading centers, earthquake swarms are generally associated with normal faulting (Sykes, 1967) and with major strike-slip faulting (Tatham and Savino, 1974). This variable mechanism indicates that volcanism is not itself the direct cause of the swarm but acts as a trigger and controlling factor.

Historical data strongly suggest that much of the activity is of the swarm-type and is related to volcanism for the Madinah earthquake (1256). Also, to the tectonism for the 1068 earthquake (Barazangi, 1981). Ben-Menahem (1979) indicated that about 26 major earthquakes (6.1 <M_L< 7.3) occurred in southern Dead Sea region between 2100 B. C. and 1900 A. D. Instrumental seismicity of the Gulf of Aqaba shows that 25000 earthquakes (1.5 <M_L< 6.1) are reported to have occurred in the period from 1965 to 1995 (Fig. 1).

In January 1983, an earthquake swarm of the Gulf of Aqaba lasted for more than four months. It indicates that the seismicity of the Dead Sea transform is characterized by both mainshock and aftershock as well as swarm types of activity

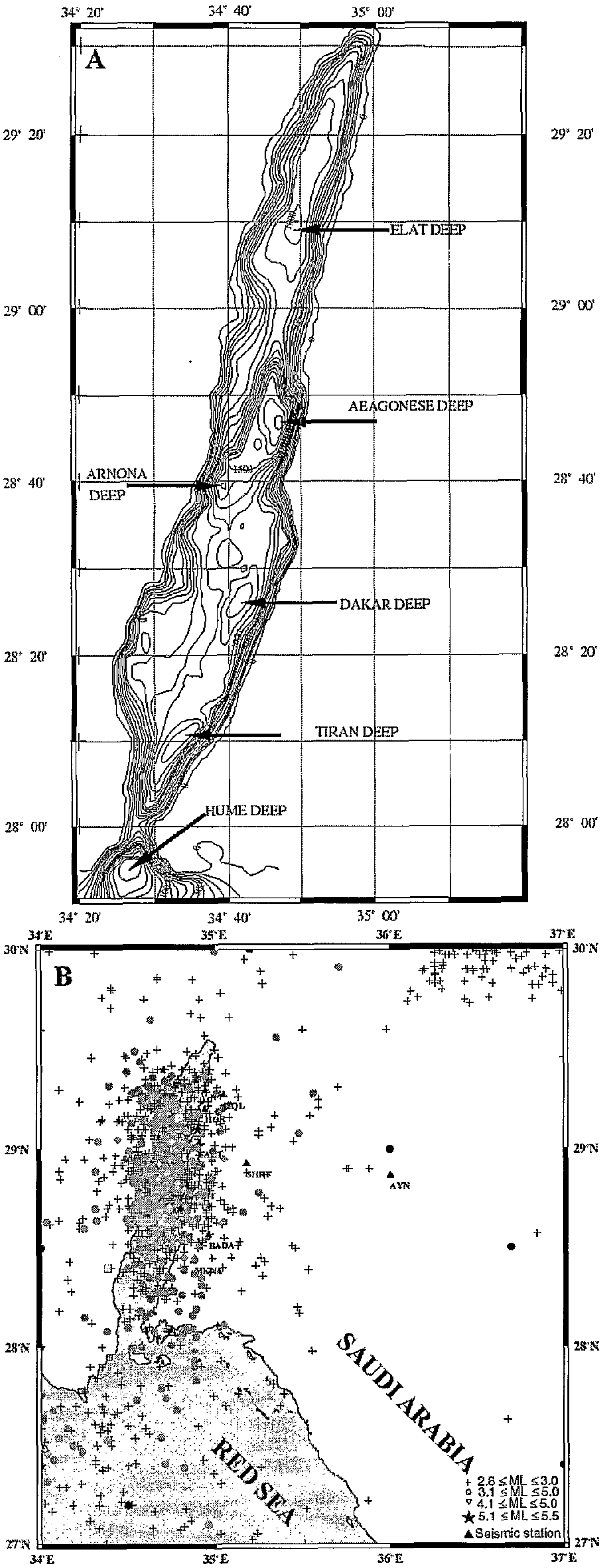

Fig. 1 *Shows a) Bathmetery map of the Gulf of Aqaba, and b) Seismicity map of the northern Red Sea.*

(El-Isa *et al.,* 1984). The swarm was associated with a maximum magnitude of 4.8 followed by more than 500 event with M_L < 3. This activity indicates a cyclic pattern of events consisting of seismic minima which may represent episodes of accumulation of energy, and seismic maxima which represent the release of energy (Bazzari *et al., 1 990).* The spatial distribution of 1983 epicenters 10-50 km south of Elat deep, overlaps with the 1985 sequences indicating that these events are representative of activity at the southern flank of the Elat deep. The largest 4 shocks in 1983 and 1985 have S-P times in the range 3-5 seconds from Haql station. Four epicentral distances equal to 20, 24, 30 and 40 km were determined for the values of S-P 3, 3.5, 4, and 5 seconds, respectively with their centers at Haql station (HQL). The farthest two shocks in 1990 and 1991 lie 10 km west of Dakar deep and their epicentral distance is about 80 km from HQL. In 1990, 245 events with M_L<4.2 are reported to have occurred and 113 events with M_L<4.1 occurred in 1991 (Al-Arifi, 1996).

Two additional earthquake swarm sequences in April 1990 and in May 1991, had maximum magnitudes of 4.1. In July 1993, an earthquake swarm began in the Gulf as a foreshock sequence and was followed by the mainshock of M_D = 5.5 on August 3. The mainshock was followed by nearly 15000 events with M_D > 1.5 in the next five months of 1993 (Al-Arifi, 1996). The sequence of 1993 began in July near Aragonese deep with a moderate increase in the frequency of background seismic activity followed by the mainshock on August 3 at 12:42 U.T.C with a magnitude 5.5 recorded by more than 120 local and regional stations (Al-Arifi, 1996). This swarm was characterized by a peak of activity followed by a quiescence and lasted until December 1993. Most of the activity concentrated 20 km SW of Aragonese deep with focal depths between 15-20 km, migrated southward in October and reoccurred in the Aragonese deep in November and December 1993.

The most recent sequence activity began in November 22, 1995 in the central part of the Gulf of Aqaba with a maximum magnitude of M_D = 5.9. More than 8000 aftershocks (1.5 <M_D< 5.9) were recorded in 100 days following the mainshock. Klinger *et al.* (1997) used 26 broadband teleseismic digital data for this swarm to perform a body wave inversion and to estimate surface rupture observed on the coastal area of the Gulf of Aqaba. Fayez (2000) used four portable short-period seismic station for this swarm from 24 November 1995 to 3rd of January 1996. The largest event (M_D = 5.9) on November 22 had an origin time of 04:15 U.T.C., a latitude of 28.8° N and longitude 34.7° E. The event was followed by more than 8000 aftershocks (1.5 <M_D< 5.9) in the next 100 days in the central part of the Gulf of Aqaba between Elat and Aragonese deeps.

The purpose of this study is to understand the focal mechanism of the recent Northern Red Sea sequences of August 1993 and November 1995 and to associate these sequences with faulting types that were found before using different methods from the data collected by portable seismographs and telemetred network of King Saud University (KSU) and King Abdulaziz City for Science and Technology (KACST) and correlating the recent seismicity of the region with the pre-existing tectonic and active faulting.

METHODOLOGY

The applied initial P-wave method assumes that the source mechanism of an earthquake is faulting and it is represented by a double couple source (Stauder, 1962). P-waves travel faster than S-wave and Surface waves. It is always responsible for the initial motion observed on a seismogram. Therefore, the particle motion of direct P-waves is not altered in the earth due to they are in the direction of propagation. The focal sphere for a seismic point source is hypothetical small sphere surrounding the focus. It is a convenient device for displaying radiation patterns since information recorded by seismographs distributed over the earth's surface may be transferred to the focal sphere. Tracing the rays back from stations to the source can do this. In tracing a ray back to the source, the observed first motion at a station is plotted on the stereo-graphic projection at the azimuth of the station with respect to the epicenter, and the angle of incidence at the focus. The polarity data give a good opportunity to have a reliable fault plane solution for the northern Red Sea region. Necessary parameters for fault plane solutions are calculated using a computer program "Hypoinverse", this program calculates the azimuth and takeoff angle and gives the data ready for plotting on lower hemisphere of the focal sphere. The program for plotting stereo-graphic projection and nodal planes call (Sphere) on a Wulff net.

SOURCE OF DATA

In the present work, sixty seven earthquake mechanism solutions are obtained depending on the available local analog records and data collected from regional stations reported in NEIC. The total of 67 earthquakes have been used to obtain the fault plane solutions of the northern Red Sea. Locations of these earthquakes are shown in figure (2a, 2b), while list of the earthquakes and their parameters are shown in table (1). Maximum and minimum focal depths for the recent earthquake data are 25 and 2 km respectively.

RESULTS AND DISCUSSION

The occurrence of earthquake sequences in 1983, 1985, 1993 and 1995 in the Gulf of Aqaba brought to attention to the hazards that may result from offshore and onshore seismic sources. It could imply that the Gulf of Aqaba (northern Red Sea) is a region of moderate to high seismic hazard. The seismicity map indicates a concentration of seismic activity in the area located between latitude 28.5°-29.1° N and longitude 34.7°-34.9°E. This high activity may be due to the thick sediments on the land beneath coastal area or to the deeps in the step zones which are sites of stress concentration, especially in the area between Elat and Aragonese deeps where some active normal and strike slip faults interact resulting in heterogeneous physical conditions within the crust.

The most remarkable aspect of the earthquake sequence in the gulf is the spatial distribution overlapping of 1995 sequence with earthquake sequences in 1983, 1985, 1991, and 1993 and the migration of the epicenters north and northeastward about 50 km in 100 days with focal depths less than 10 km confirming the continual recent crustal motion along the southern portion of Dead Sea transform system. The locations of the 1995 epicenters indicate a clear overlap with the 1993 sequence west of Aragonese deep, suggesting that one tectonic unit is located in the area between Elat and Aragonese deeps. The remaining excess strain energy after 1993 was released by the 1995 sequence. Al-Arifi (1996) indicates that local isostatic adjustments in the fault system in the Gulf of Aqaba result in the uplifting of crustal rocks that disturbs the stress regime and causes a gradual stress release as in swarm-type activity.

Field geologic measurements indicate past faulting and confirm the activity on the land (Rowaihy, 1984). High-pass filtering was applied in image processing techniques to prove fault extension and fractures. Strong dominance of lineaments are in NE-SW directions which are in good agreement with the regional trend of the Gulf of Aqaba. Comparison of observed lineaments with previously mapped features showed that many of them coincide with mapped faults (Al-Arifi, 1996).

In addition to local and portable seismic stations (20 stations) of KSU and KACST, some other stations in the west, northwest and north of the gulf were used to obtain a reliable first motion direction and fault plane solutions. Some of the observed first motions of the swarm were not easy to be identified because of limited dynamic range in analog recording and all stations are equipped with short-period vertical seismometers. Consequently, it was difficult to obtain reliable fault plane solutions.

However, a fault-plane solutions were determined using the polarities of P arrivals recorded at more than forty stations within 300 km of the epicenter. A total of sixty seven single event focal mechanisms (Fig. 2a, 2b) for main and aftershocks were carried out for the largest magnitudes ($2.5 < M_D < 5.9$). All events are located in the Gulf of Aqaba. The mainshock of August 3rd of $M_D = 5.5$ indicates normal faulting on planes striking N22° E. Most of aftershocks shows also normal faulting on planes having the same azimuth. The mainshock of November 22 of $M_D = 5.9$ indicates strike-slip faulting on planes striking N 9° W. The first aftershock of November23 ($M_D = 5.3$) showing strike-slip faulting (N 79° E) with a component of thrust faulting. Both events occurred in the Aragonese deep. The second and third aftershock occurred around lat. 29° N between Elat and Aragonese deeps. They indicate strike-slip faulting on planes striking N15°-48° E. The forth aftershock of November 24 ($M_D = 4.8$), occurred in the southern flank of the Elat deep. It indicates nearly pure strike-slip faulting on planes striking N 3° E (Fayez, 2000).

Generally, the results obtained from the above fault-plane solutions indicate strike-slip faulting on planes striking N to NE and dipping 40°-70° to the northwest and northeast. They are in good accordance with the three focal mechanism solutions of November 22 earthquake obtained by Klinger *et al.* (1997). The body wave inversion (Klinger *et al.,* 1997) and the location of the aftershocks demonstrates that November 22 rupture is formed by the successive breaking of three segments oriented N-S. They suggest that the rupture is propagating toward the north, jumping to the left from one segment to the next along E-W structures. This is in good agreement with the previous models (Ben-Avraham, 1985; Al-Amri *et al.,* 1991; Al-Arifi, 1996; Fayez, 2000) of pull-apart basins for the Gulf of Aqaba.

It is believed that the low level of seismic activity south of latitude 28.5° N compared with the northern segment of the Gulf of Aqaba could be due to the lithospheric deformations in this region are occurring on land. The most direct evidence to support the this assumption is the occurrence of some large historical earthquakes in 641, 1068, 1256, 1293, and 1588 which are reported to have been felt causing ground cracking and widespread destruction.

CONCLUSIONS

It can be concluded from this study that the seismic activity along the Gulf of Aqaba occurs in the form of sequences, each lasting up to several months. reaching peak magnitude up to 7.0 and covering a specific tectonic segment of the gulf. Places of interaction of normal and strike-slip faulting at the southern flank of the Elat deep could be the sites of sequence sources and stress accumulations in the 1980's and 1990's. A clustering of sequence activity in time may suggest an episodic source of strain or a constant source with repeated slip along the fault zone. Geologic field measurements observed after November 22, 1995 earthquake and seismic data provide evidence for continuation of the faulting regime from the gulf NE and NW into the land causing significant seismic hazard.

The principal mode of faulting, as determined by all single focal mechanism solutions of mains and aftershocks was strike-slip faulting on planes striking NE and dipping 40-70° to NW-NE and normal faulting on planes striking NE-E and dipping 40-50° to NW-SE. This result is what would be expected from the regional left-lateral slip movement of the Dead Sea transform system and from linear surface cracking observed in the affected areas.

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Table 1 List of events used for the single fault plane solution and their hypocentral parameters, fault plane parameters.

Date	time	lat. N	long. E	depth	strike1	dip1	rake1	strike2	dip2	rake2	Type of faulting
93/08/03	12:42:43	28.628	34.644	22.0	021	34	-080	190	57	-97	Normal^{+}.
93/08/03	16:33:26	28.760	34.700	10.0	142	13	-123	356	79	-83	Normal^{+}.
93/08/06	06:51:26	28.738	34.518	12.0	008	28	-153	254	77	-64	Normal^{+}.
93/08/06	22:05:23	28.699	34.700	17.0	078	87	-077	183	14	-165	Normal^{+}.
93/08/07	10:25:24	28.705	34.739	15.0	024	42	-081	192	49	-098	Normal.
93/08/12	07:08:04	28.637	34.601	15.0	044	46	-080	209	45	-101	Normal.
93/08/12	19:00:43	28.672	34.673	12.0	103	69	-117	337	34	-040	Normal^{+}.
93/08/15	15:35:03	28.766	34.743	19.0	034	59	-067	174	38	-123	Normal^{+}.
93/08/16	11:14:39	28.701	34.614	11.0	121	65	-093	309	25	-083	Normal.
93/08/16	16:29:21	28.674	34.774	23.0	034	48	-062	176	50	-117	Normal^{+}.
93/09/04	10:07:16	28.633	34.740	17.0	050	58	-074	201	36	-114	Normal^{+}.
93/09/07	06:48:46	28.701	34.778	20.0	041	61	-077	196	32	-122	Normal.
93/09/08	16:12:09	28.636	34.707	18.0	195	23	-029	312	79	-110	Normal^{+}.
93/09/13	00:13:54	28.662	34.518	05.0	061	87	-086	185	04	-146	Normal^{+}.
93/09/14	18:02:14	28.124	34.734	26.0	010	81	-127	269	38	-015	Normal^{+}.
93/09/15	02:46:52	28.652	34.719	15.0	021	21	-090	201	69	-090	Normal.
93/09/16	05:41:38	28.651	34.716	23.0	057	68	-067	188	32	-134	Normal^{+}.
93/09/20	01:34:15	28.693	34.763	21.0	057	71	-067	185	30	-139	Normal^{+}.
93/09/20	20:18:02	28.663	34.597	09.0	068	50	-131	302	55	-052	Normal^{+}.
93/09/25	12:38:10	28.628	34.782	20.0	049	57	-065	189	40	-123	Normal^{+}.
93/09/26	16:25:10	28.705	34.663	18.0	078	87	-077	183	14	-165	Normal^{+}.
93/09/26	23:19:02	28.642	34.708	20.0	057	64	-059	183	40	-173	Normal^{+}.
95/11/26	02:25:45	28.780	34.773	13.0	190	35	-100	022	56	-083	Normal.
95/11/29	01:39:01	29.157	34.786	03.0	255	45	-070	048	48	-109	Normal.
95/11/29	01:54:04	28.736	34.919	02.0	195	85	100	311	11	027	Normal^{+}.
95/12/02	21:46:54	29.050	34.858	04.0	235	40	-100	068	51	-082	Normal.
95/12/03	07:54:58	28.826	34.686	02.0	275	50	-070	065	44	-112	Normal.
95/12/03	08:49:39	29.164	34.719	06.0	065	85	-100	309	11	-027	Normal^{+}.
95/12/03	21:57:53	28.833	34.674	14.0	235	10	-100	065	80	-088	Normal.
95/12/04	02:45:28	28.738	34.685	02.0	125	60	-020	225	73	-143	Normal^{+}.
95/12/04	12:39:50	28.964	34.831	15.0	210	45	-090	030	45	-090	Normal.
95/12/07	01:00:59	29.189	34.839	12.0	170	90	-100	080	10	000	Normal^{+}.
95/12/09	06:33:52	28.713	34.807	10.0	285	60	-040	038	56	-143	Normal^{+}.
95/12/11	01:32:08	28.861	34.642	22.0	210	30	-090	030	60	-090	Normal.
95/12/11	18:35:12	28.960	34.744	20.0	225	75	-040	357	52	-161	Normal^{+}.
95/12/12	14:09:18	28.780	34.788	16.0	095	35	-110	299	57	-077	Normal.
95/12/15	06:00:08	28.771	34.775	02.0	255	30	-070	052	62	-101	Normal.
95/12/18	16:57:40	28.952	34.756	18.0	250	75	-040	352	52	-161	Normal^{+}.
95/12/23	06:28:54	29.181	34.925	19.0	135	90	110	225	20	000	Normal^{+}.
95/12/30	05:13:39	28.904	34.688	22.0	250	25	-050	027	71	-107	Normal.
96/01/01	17:17:45	29.250	34.665	06.0	255	30	-050	031	67	-110	Normal.
96/01/02	03:22:35	28.920	34.842	17.0	175	25	-170	076	86	-065	Normal^{+}.
96/01/02	19:14:47	28.800	34.795	08.0	220	45	-030	332	69	-131	Normal^{+}.
96/02/21	04:59:51	28.800	34.780	15.0	132	30	-104	328	61	-068	Normal.
93/07/30	23:34:10	28.739	34.715	27.0	222	37	123	003	60	068	Left-lateral Strike-slip^{+}.
93/08/09	06:05:04	28.749	34.682	12.0	063	37	-147	306	71	-057	Left-lateral Strike-slip^{+}.
93/08/15	15:10:11	28.753	34.729	18.0	295	56	174	029	85	035	Left-lateral Strike-slip.
93/08/15	15:38:45	28.767	34.753	12.0	207	90	087	117	03	-180	Left-lateral Strike-slip^{+}.
93/08/16	16:48:28	28.747	34.660	01.0	303	37	173	038	86	053	Left-lateral Strike-slip.
93/09/06	20:37:45	28.615	34.501	10.0	202	22	053	061	72	104	Left-lateral Strike-slip^{+}.
93/09/07	16:40:42	28.723	34.718	21.0	320	73	078	178	21	126	Left-lateral Strike-slip^{+}.
93/09/10	13:57:14	28.772	34.572	07.0	188	12	016	082	87	102	Left-lateral Strike-slip^{+}.
93/09/10	20:09:07	28.653	34.541	08.0	239	90	174	329	84	000	Left-lateral Strike-slip.
93/09/13	00:03:00	28.673	34.652	12.0	235	60	103	030	32	068	Left-lateral Strike-slip^{+}.
93/09/13	09:56:46	28.615	34.750	19.0	313	78	079	177	16	133	Left-lateral Strike-slip^{+}.
93/09/15	01:43:22	28.685	34.000	01.0	282	53	145	035	63	042	Left-lateral Strike-slip.
93/09/18	08:35:27	28.693	34.599	17.0	188	31	033	089	74	117	Left-lateral Strike-slip^{+}.
93/09/25	08:19:47	28.637	34.712	21.0	313	82	120	056	31	016	Left-lateral Strike-slip^{+}.
93/11/20	11:35:56	28.752	34.482	05.0	193	05	033	070	88	094	Left-lateral Strike-slip^{+}.
95/11/22	04:15:11	28.820	34.860	12.0	196	59	-015	294	77	-148	Left-lateral Strike-slip.
95/11/22	22:16:55	28.606	34.810	05.0	202	67	-003	293	87	-157	Left-lateral Strike-slip.
95/11/23	18:07:56	29.273	34.762	05.0	199	77	007	107	83	167	Left-lateral Strike-slip.
95/11/26	11:36:37	29.193	34.819	21.0	190	85	050	094	40	172	Left-lateral Strike-slip^{+}.
95/12/03	15:07:09	28.679	34.623	02.0	110	90	-180	200	90	000	Left-lateral Strike-slip.
95/12/07	20:32:14	28.405	34.659	09.0	075	20	-180	165	90	070	Left-lateral Strike-slip^{+}.
95/12/19	12:32:50	28.820	34.667	15.0	230	70	-150	129	62	-023	Left-lateral Strike-slip.
96/01/03	10:05:29	28.600	34.850	18.0	175	65	040	065	54	149	Left-lateral Strike-slip^{+}.

Normal^{+} = Normal with minor component of strike-slip. Left-lateral Strike-slip^{+} = Left-lateral Strike-slip with minor component of dip-slip

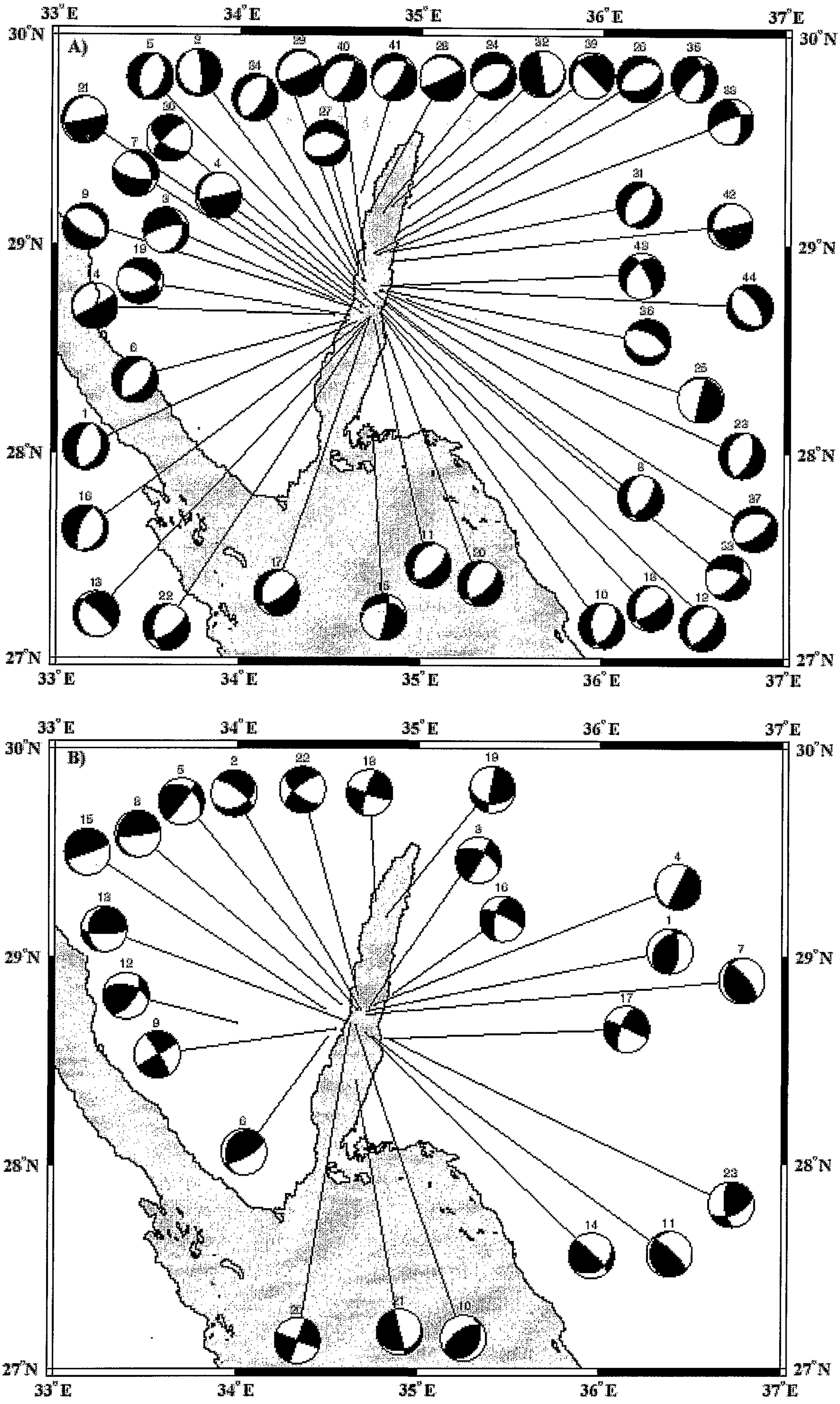

Fig. 2 Location map of events A) that have a normal faulting or normal faulting with minor strike-slip component, B) that have left-lateral strike-slip faulting or left-lateral strike-slip faulting with minor component of dip-slip.